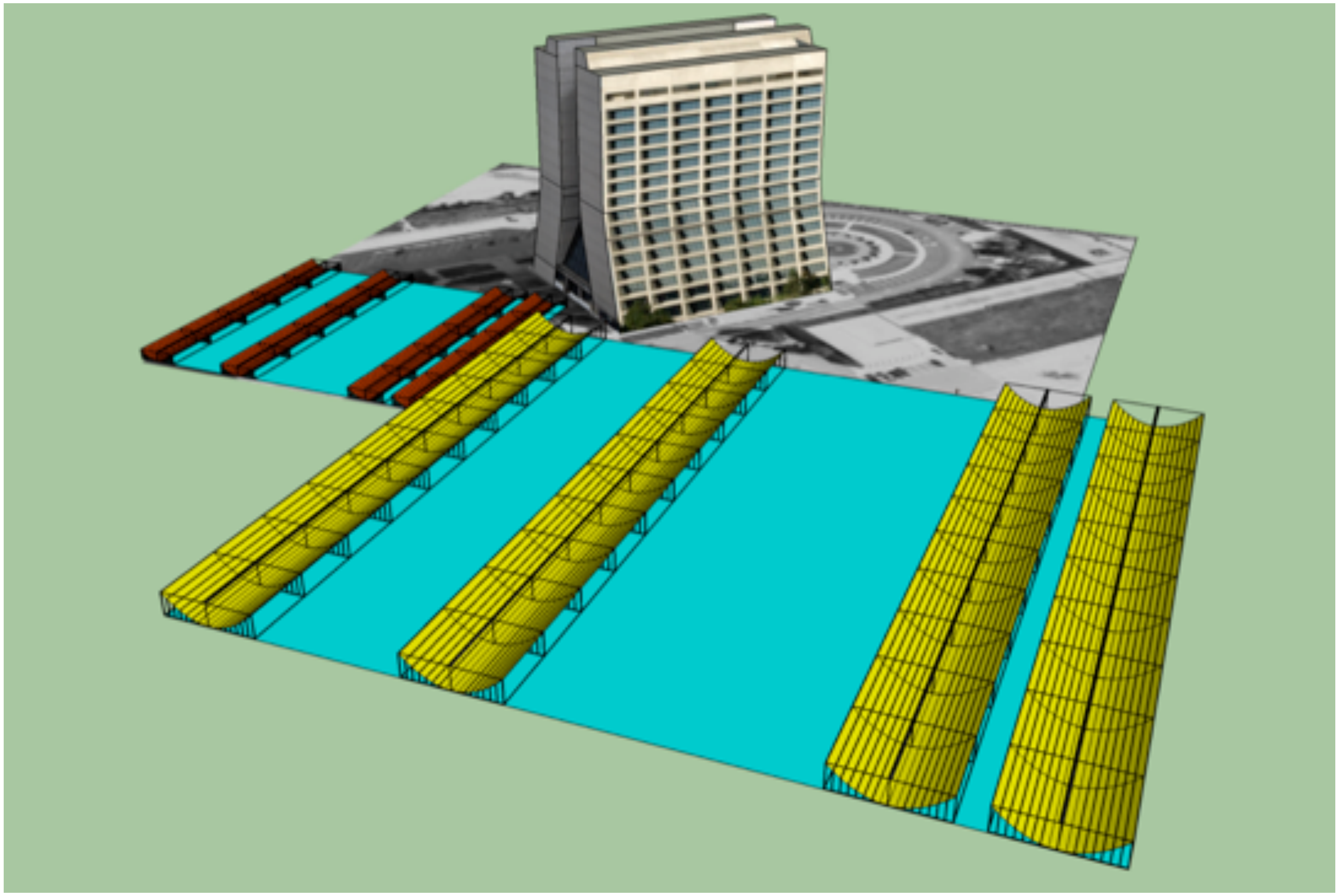
CRT@FNAL: Science Motivation

Probing Dark Energy with Intensity Mapping of HI 21cm Emission



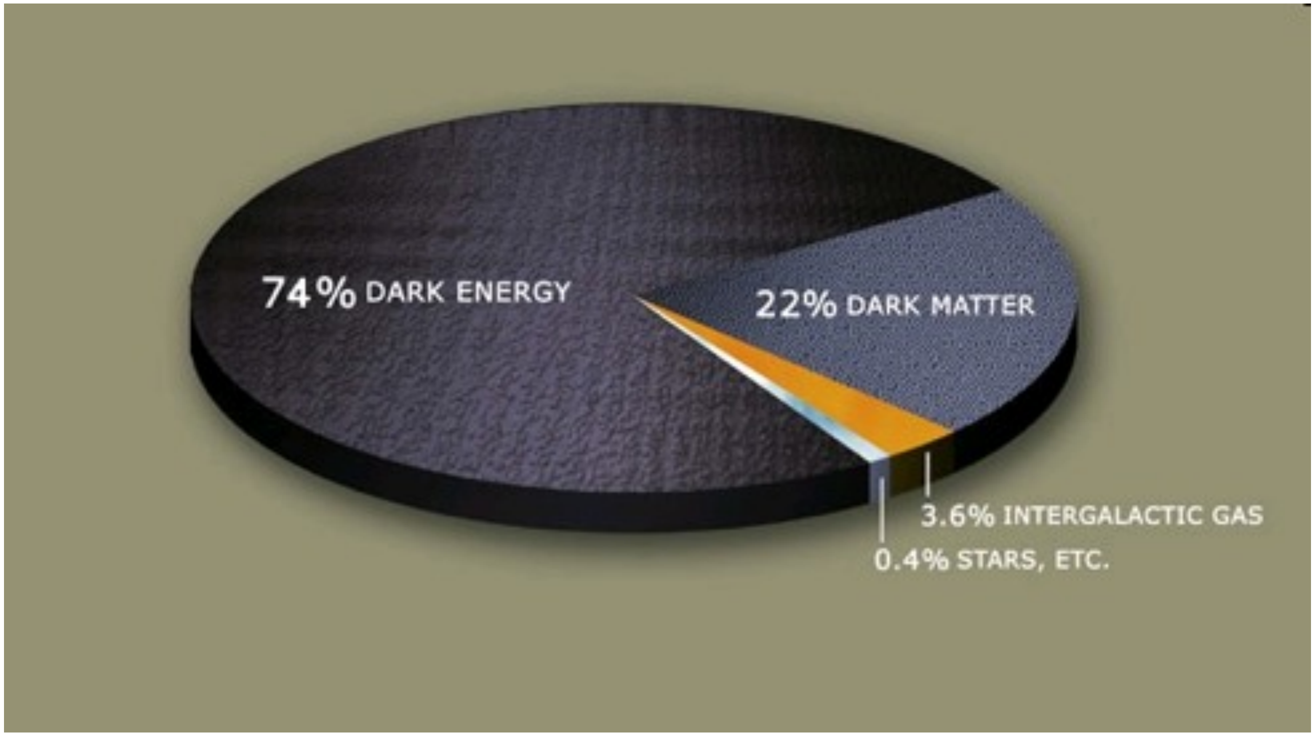
21 cm External Review
6/3/10

Albert Stebbins
FNAL

Cosmology @ FNAL

Fundamental Physics From Cosmology

Dark Sector



Dark Energy @ FNAL

"Biggest Mystery in the Universe"

Not only because it is 75% of the stuff in the universe.
It likely has fundamental implications for particle physics and/or the nature of space and time.

FNAL & DOE have a record supporting research to characterize Dark Energy

Theory, SDSS (II), DES, SNAP/JDEM, LSST (@LLNL, SLAC).
Many projects emphasize their "dark side" (dark energy dollars).
For CRT Dark Energy is the main goal!

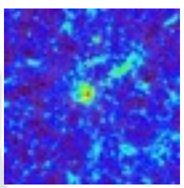
Three Pillars of DE Observational Science

SN: supernovae

- Best at low z (z<0.8)
- Purely geometric probe

BAO: baryon acoustic oscillations

- Best at high z (z>0.8)
- Purely geometric probe

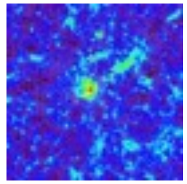


WL: weak lensing

- Probes both geometry and gravity
- Most prone to systematic errors

DE Can't Stand On 2 Legs





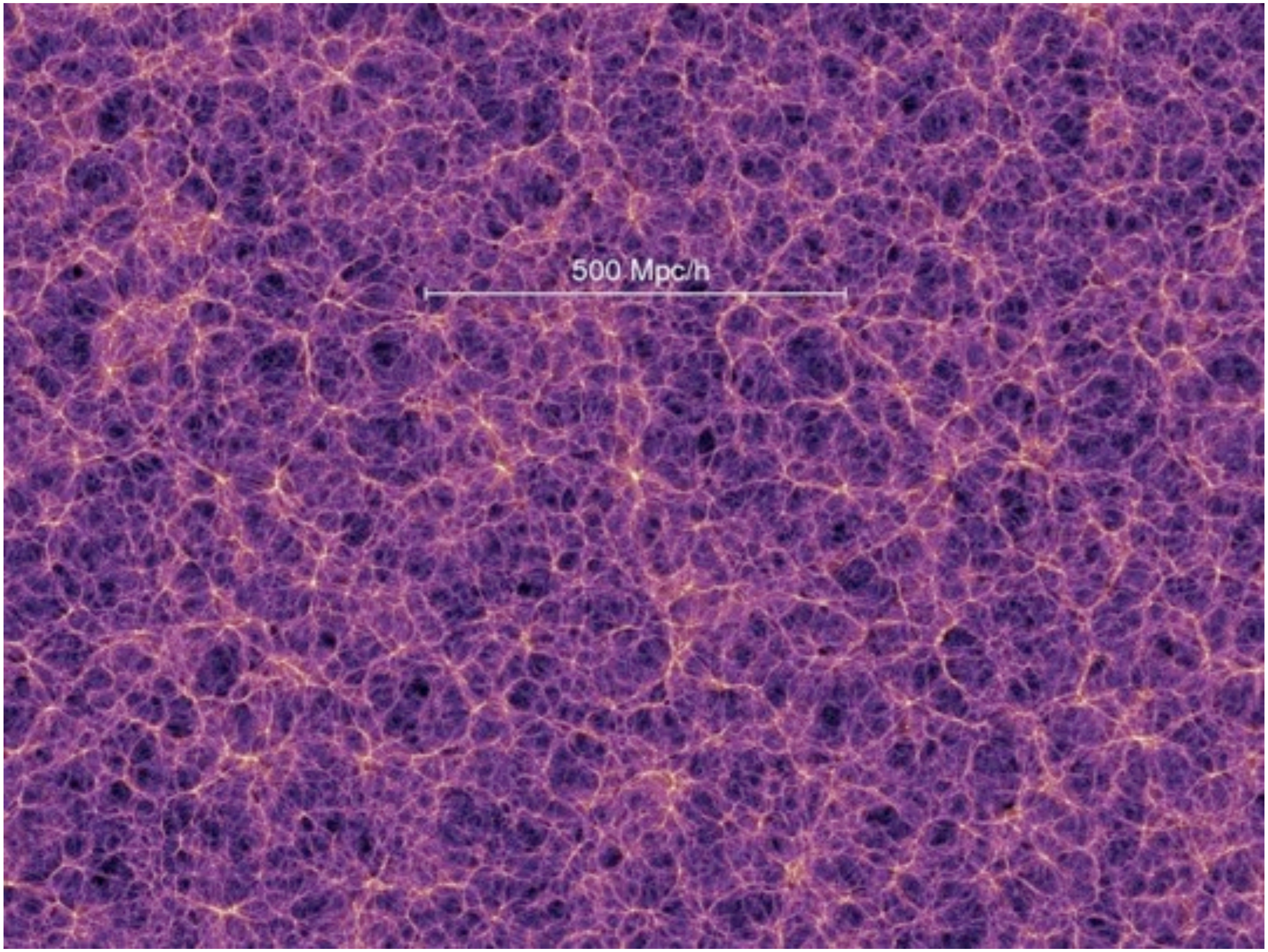
SN $z_{\max}$	SN mag err	BAO $z_{\max}$	BAO $f_{\rm sky}$	WL $N/10^9$	WL err/stat	DETF FoM	1σ err w_p	1σ err $\ln H_0$	1σ err Ω_K
0.8	0.005	3.0	0.250	1.0	2.0	975.7	0.011	0.0050	0.00036
XX	XX	3.0	0.250	1.0	2.0	295.0	0.017	0.0153	0.00040
0.8	0.005	XX	XX	1.0	2.0	418.8	0.014	0.0089	0.00201
0.8	0.005	3.0	0.250	XX	XX	667.5	0.014	0.0052	0.00048

It is also crucial to have a cross-check.

(Numbers courtesy D. Eisenstein)

Cosmology By Cartography

We study noise *i*.e. the Large Scale Structure



Millennium SImulation

Baryon Acoustic Oscillations

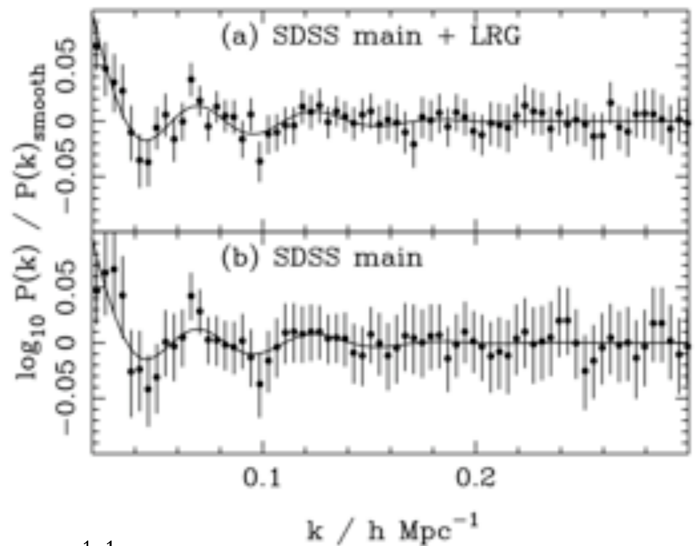
Small wiggles is in the LSS power spectrum / correlation function are the remnants of cosmic sound waves which were fossilized when the sound speed dropped rapidly at recombination.

It is presently standard procedure to focus on this unique signature of LSS - using them as a **standard ruler** to measure the expansion

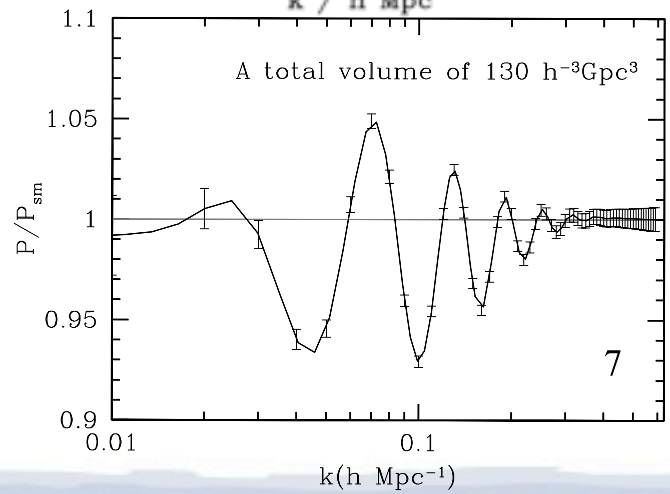
$$H[z] = \sqrt{\frac{8\pi G\,\Omega[z]\,\rho[z]}{3}}$$

$$D_{co}[z] = \int_0^z dz\,\frac{c}{H[z]}$$

$$D_{A,co}[z] = \frac{c\,\mathrm{Sin}\left[\frac{H_0}{c}\sqrt{\Omega_0 - 1}\;D_{co}[z]\right]}{H_0\sqrt{\Omega_0-1}}$$

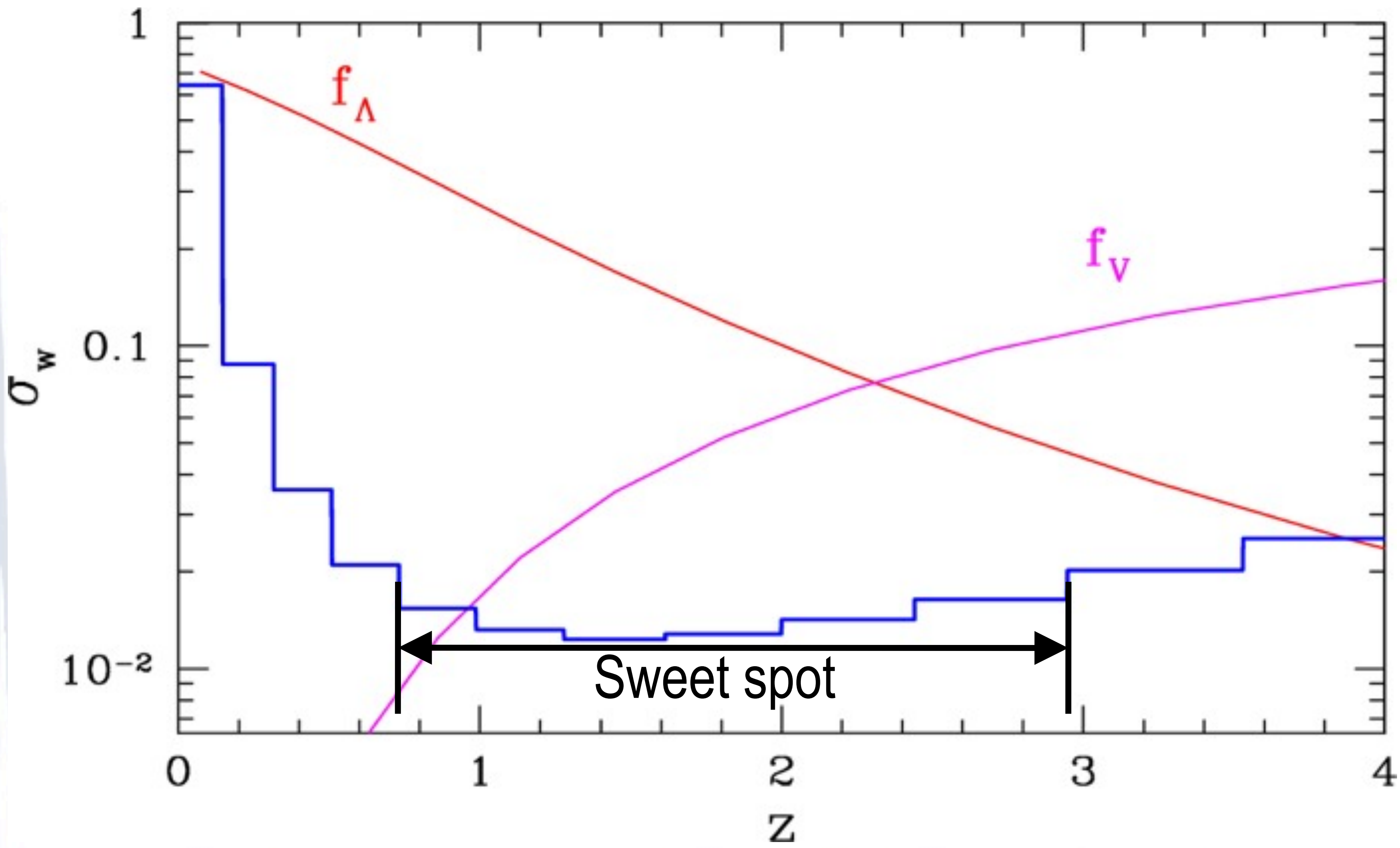


Percival et. al 2007

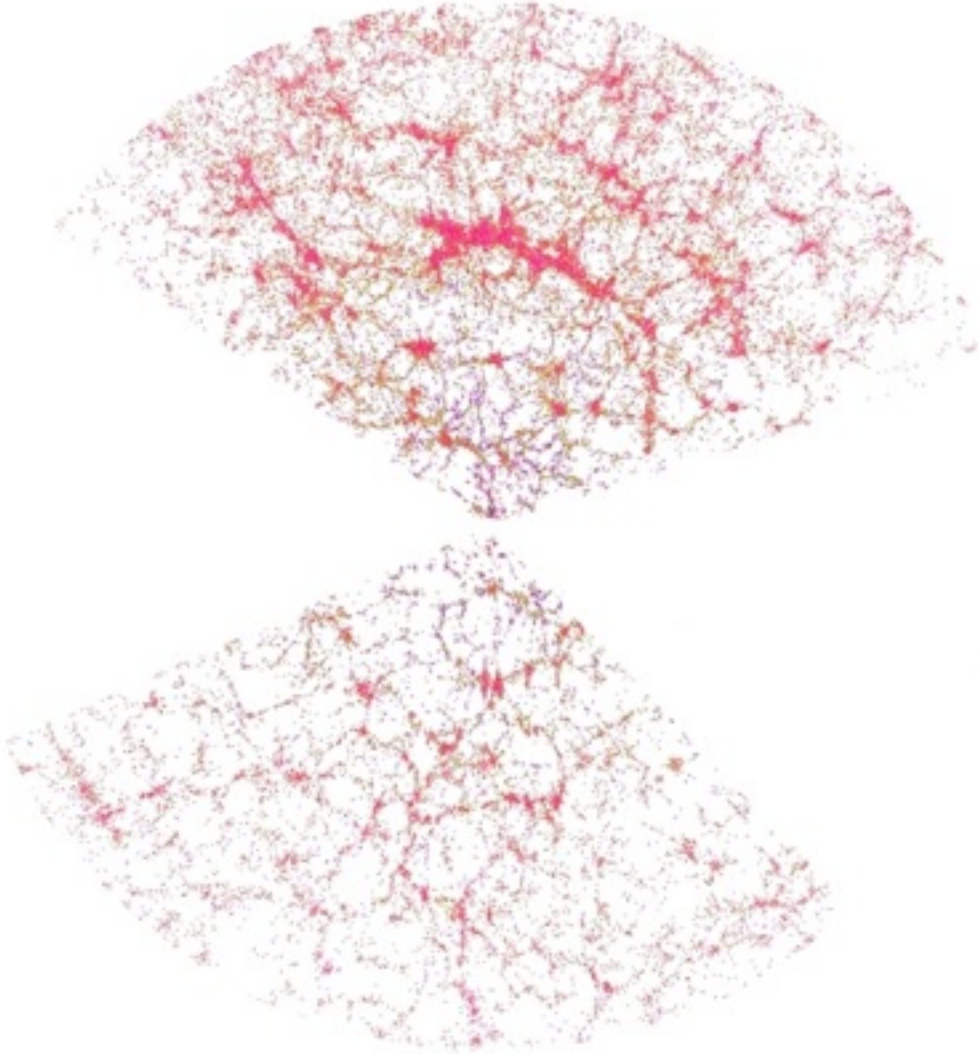


CRT Seo et. al 2010

Baryon Acoustic Oscillations

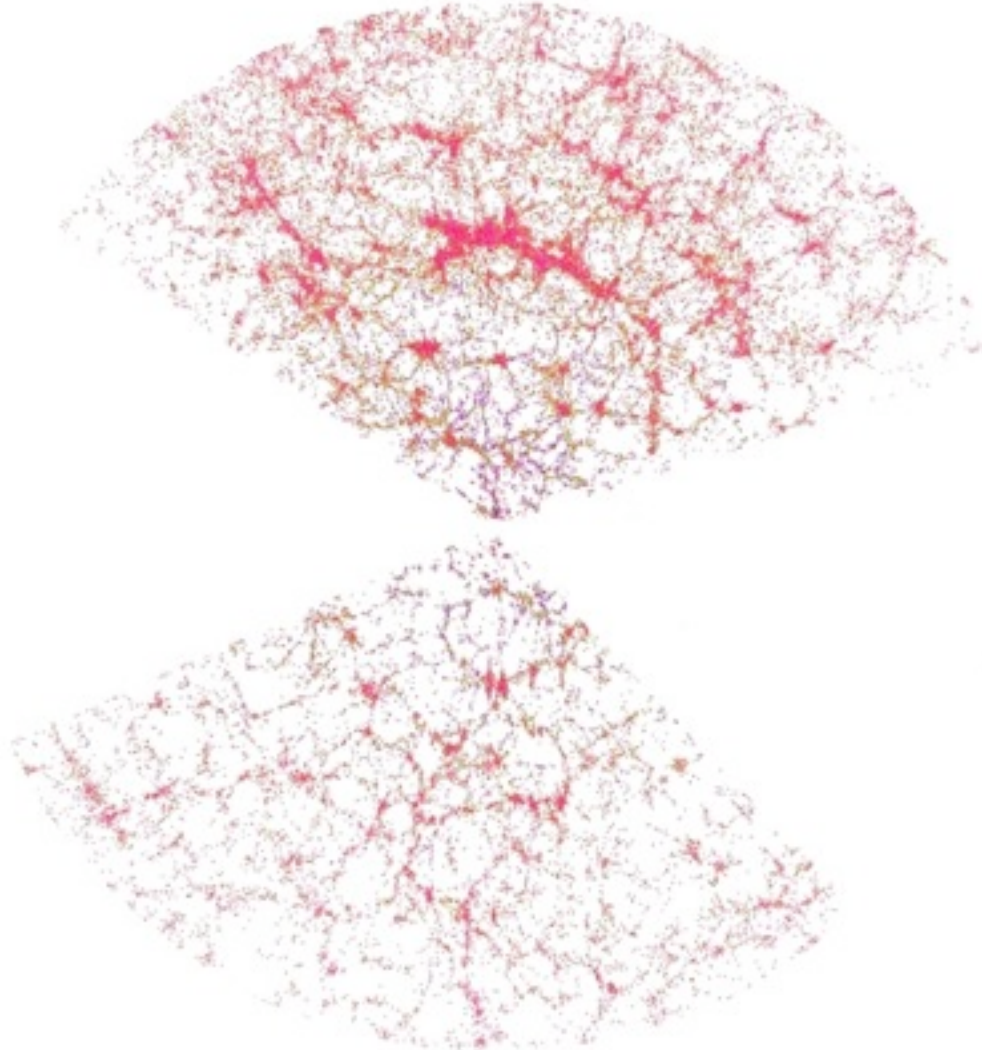


LSS in Optical / IR



multi-band: COLOR - get galaxy types

LSS in Optical / IR



multi-band: COLOR - get galaxy types 9

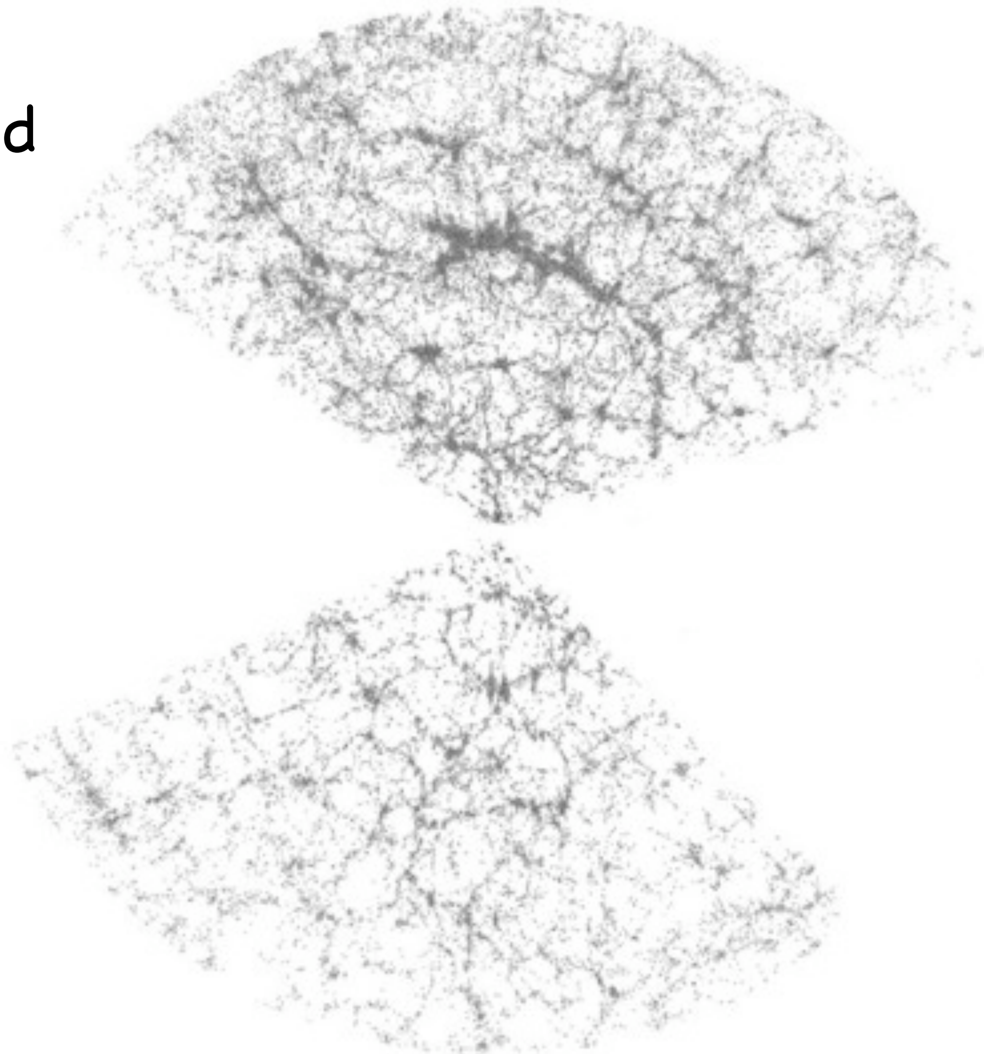
+ spectroscopic survey

LSS in 21cm

All-In-One

photometry and

spectroscopy!



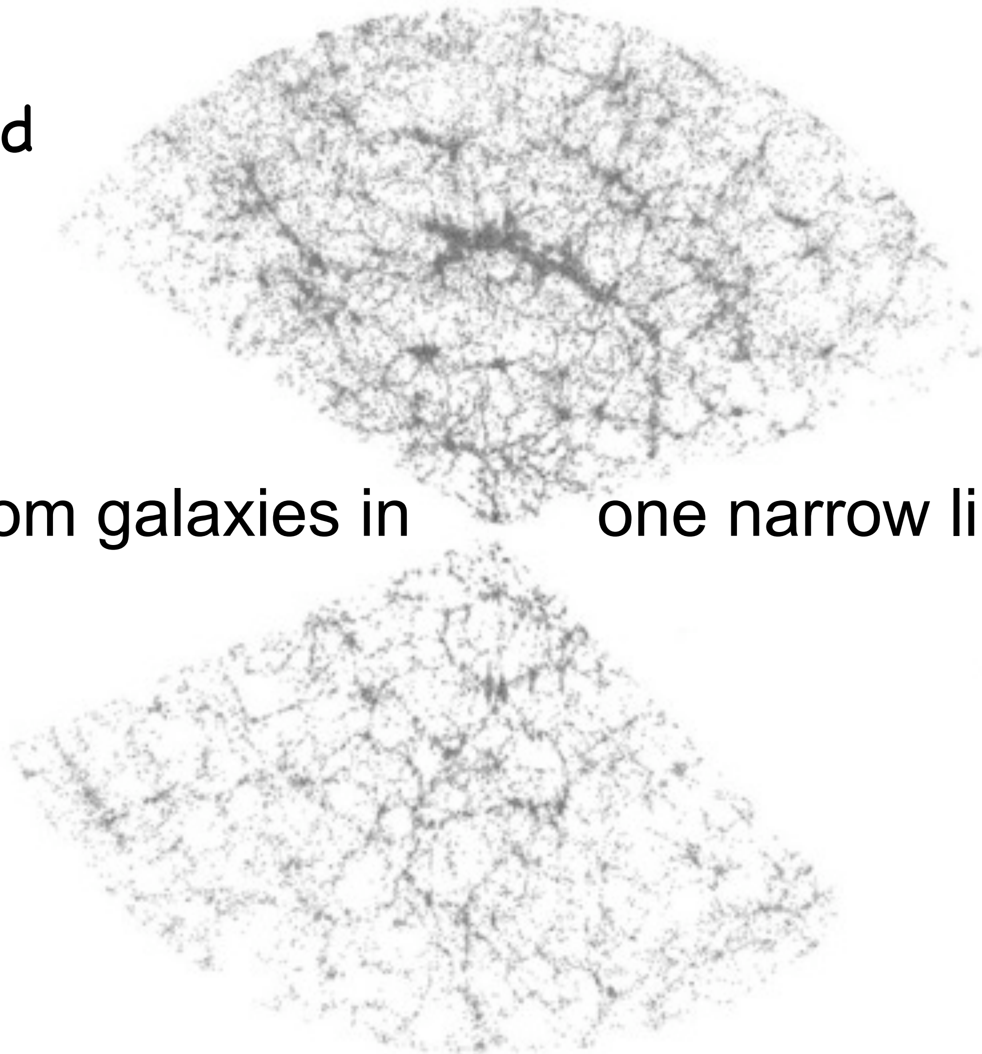
no colors - just redshifts: GRAYSCALE

LSS in 21cm

All-In-One

photometry and

spectroscopy!



all emission from galaxies in one narrow line emission

no colors - just redshifts: GRAYSCALE

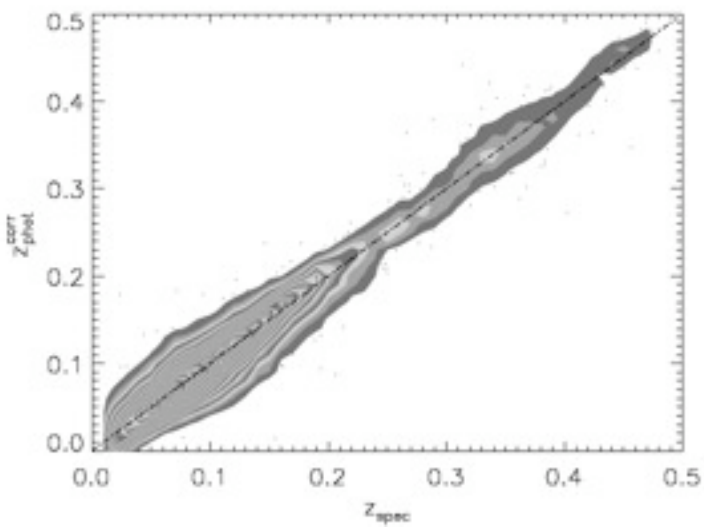
Redshift Resolution

Unlike Optical / IR for 21cm

Redshift Determination is Easy and Cheap

- FFT RF spectral analyzer of incoming signal (1GHz).
- Imaging and spectroscopy in same observation.

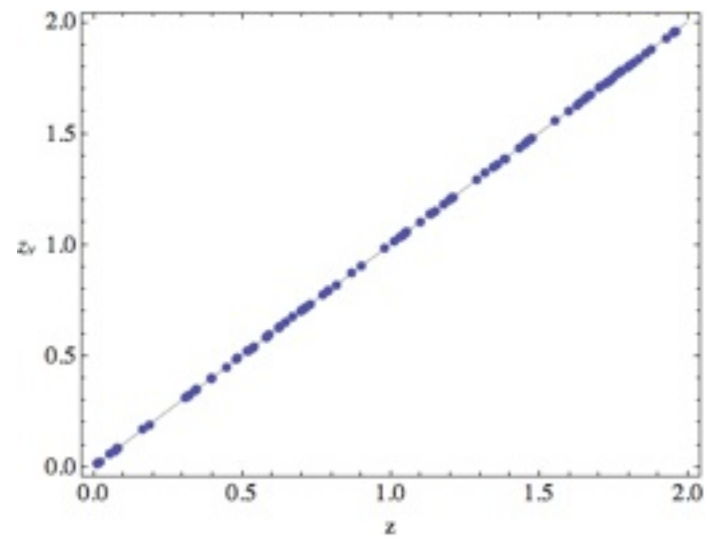
cheap photometric z



D'Abrusco 2007

versus

cheap radio z



good radial resolution

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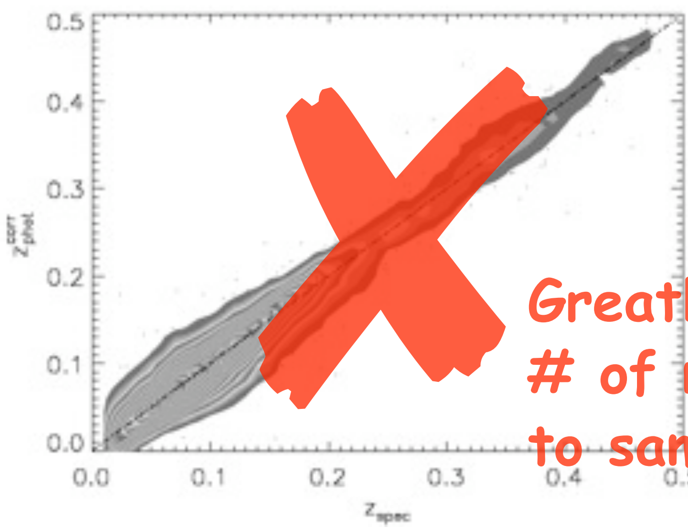
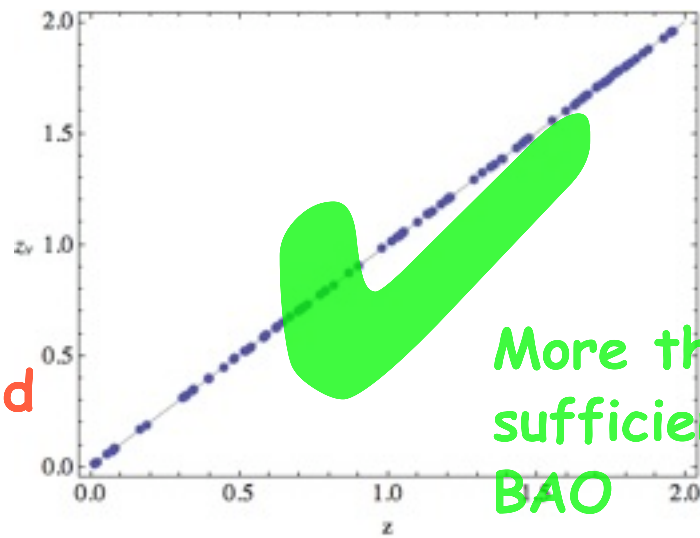


D'Abrusco 2007

Greatly limits
# of modes used
to sample BAO

versus

cheap radio z



More than
sufficient for
BAO

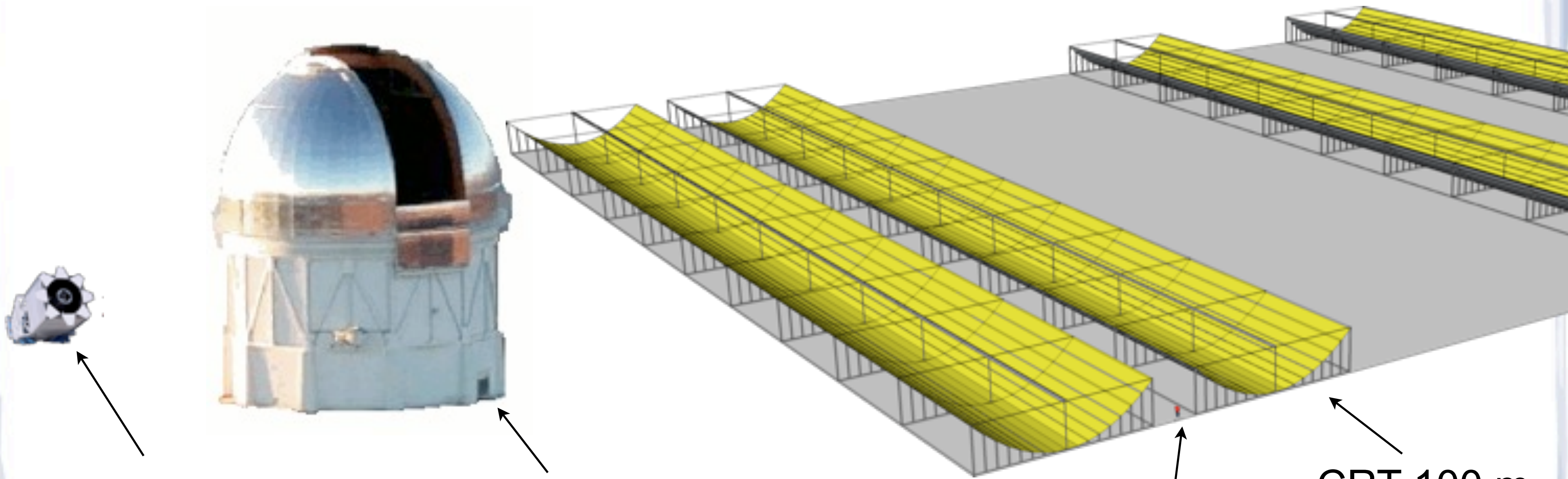
good radial resolution

$\theta \sim \lambda / D$

Angular Resolution is more challenging for 21cm than for optical / IR because of diffraction limit.

Need 100m telescope for only 10’ resolution!

Fortunately cost per unit area is small.



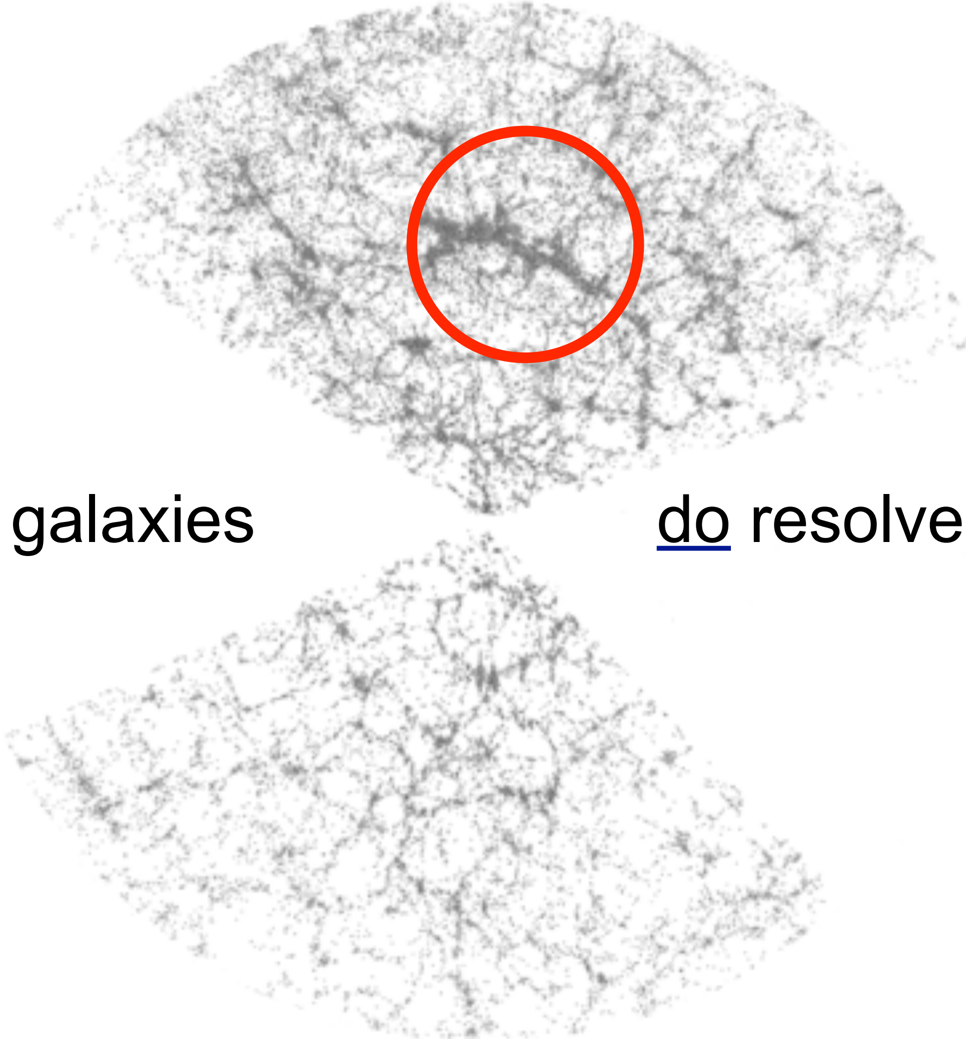
SDSS 2.5 m

DES 4 m (Blanco)

human

CRT 100 m

INTENSITY MAPPING



do not resolve galaxies

do resolve LSS / BAO

Peterson *et al* 2006

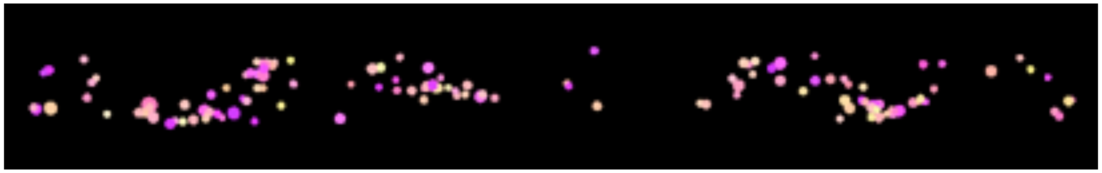
Wang *et al* 2006

Seo et al. 2010.

Expensive to resolve individual galaxies (e.g. SKA)

instead only resolve what is needed for BAO features!

INTENSITY MAPPING



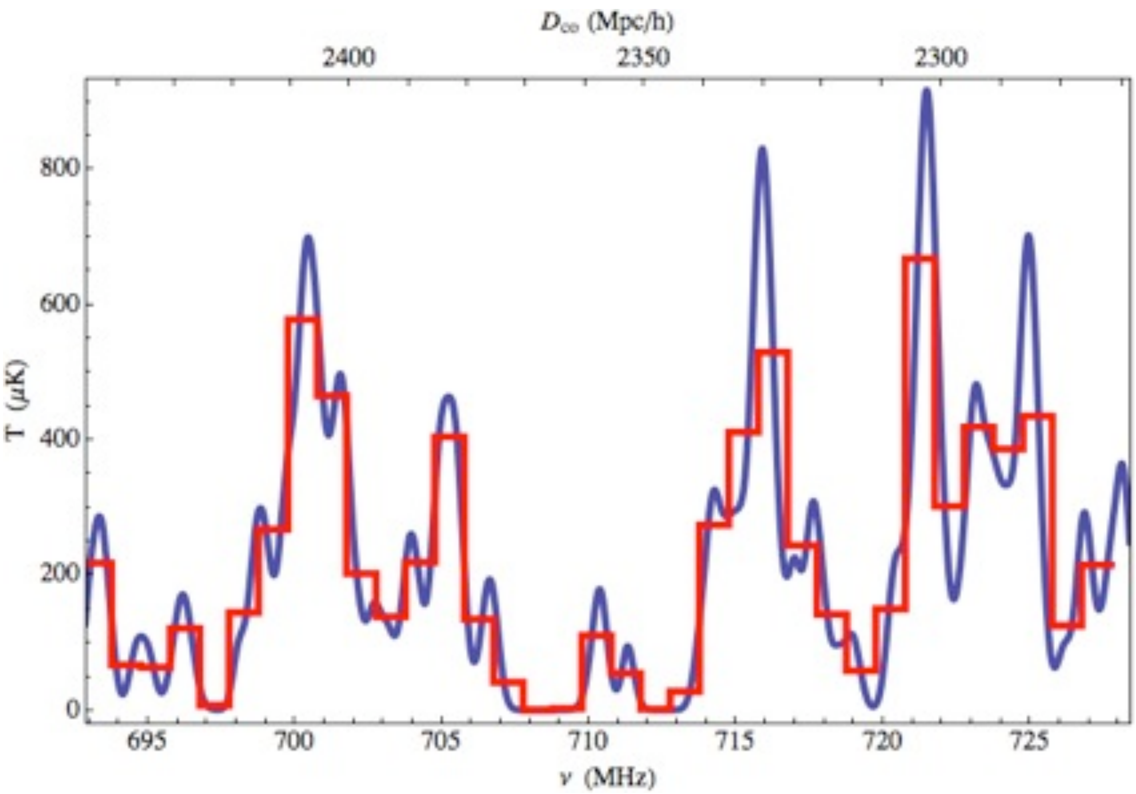
DEEP2

Δv=1 MHz

$\Delta\theta$=10'

Tully-Fisher

$M_{HI} \propto L_B$



CRT

We can nearly resolve galaxies in redshift space.

Has Anyone Done This Before?

A positive signal was found in cross-correlation between HIPASS intensity map and 2df galaxy survey (Pen et al. 2008), Green Bank Telescope and DEEP2 (Chang et al. 2010).

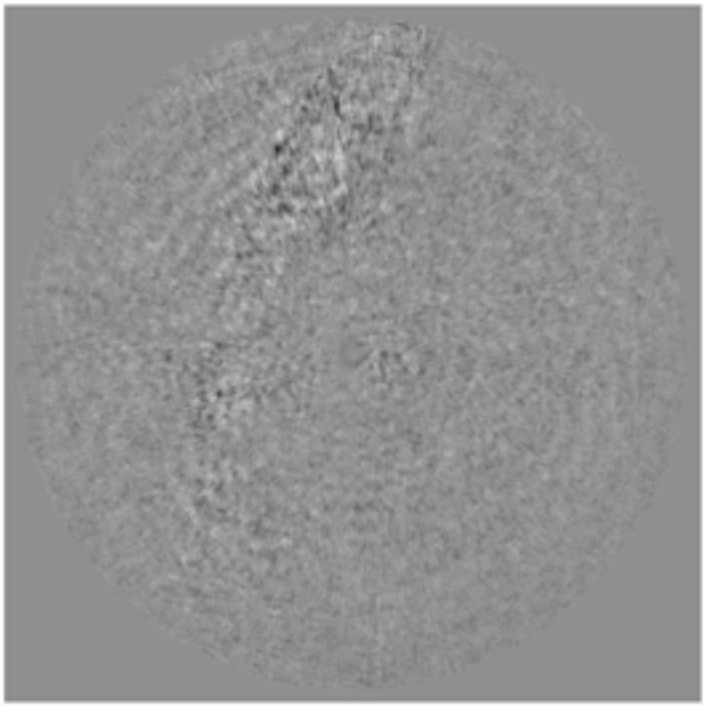


Figure 1. The HIPASS data cube $R < 127h^{-1}$ Mpc, projected in a cartesian coordinate system towards the south pole.

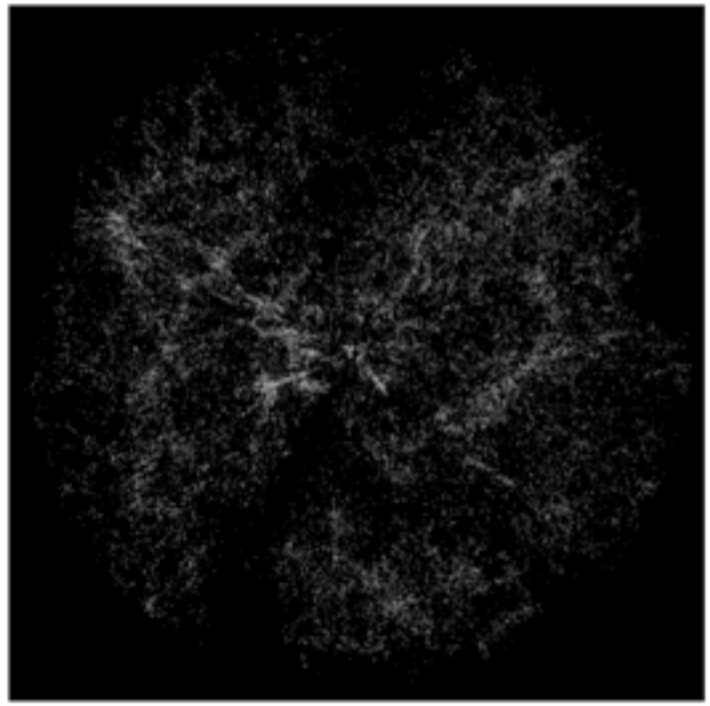


Figure 2. The 6dFGS catalog for $R < 127h^{-1}$ Mpc, also projected towards the south pole. The missing wedges are the galactic plane.

For DE one would need auto-correlation!

Why Do 21cm?

- Radio 21cm window offers a completely independent check on DE measurements, with entirely different systematics.
- In the radio we detect mostly dwarf, HI rich, slow star-forming galaxies.
- Optical-IR surveys all rely on emission line (i.e. actively star-forming) galaxies.
- Two approaches will sample two very different galaxy populations, with different biasing properties.

DE Prospects

There are different concepts for how to do a 21cm BAO survey, but generally speaking

- Unlike optical / IR - redshifts (high & low) are relatively easy (*e.g.* z ~ 0.5 - 2)
- Unlike optical / IR - very large survey areas are also easy (*e.g.* 3π steradians).
- We expect a Stage-III+ DE probe might cost $20M.

Competitive BAO Alternatives

Photometric BAO is fundamentally limited ●

- **BigBOSS** ($100M, done by 2020)
- FoM = 175 (285 with BigBoss-South)
- 14,000 (24,000) deg^2
- Based on [OII] emission line
- **JDEM** (~$650M, done by 2021)
- FoM = 250
- Full sky, cosmic variance limited
- Based on Hα emission line

Is 21cm the Future of Cosmic Cartography?

Sample variance has been one of the major limitations in using cosmic maps to accurately determine cosmological parameters!

The CRT would be the "**largest**" Large Scale Structure Survey to date.

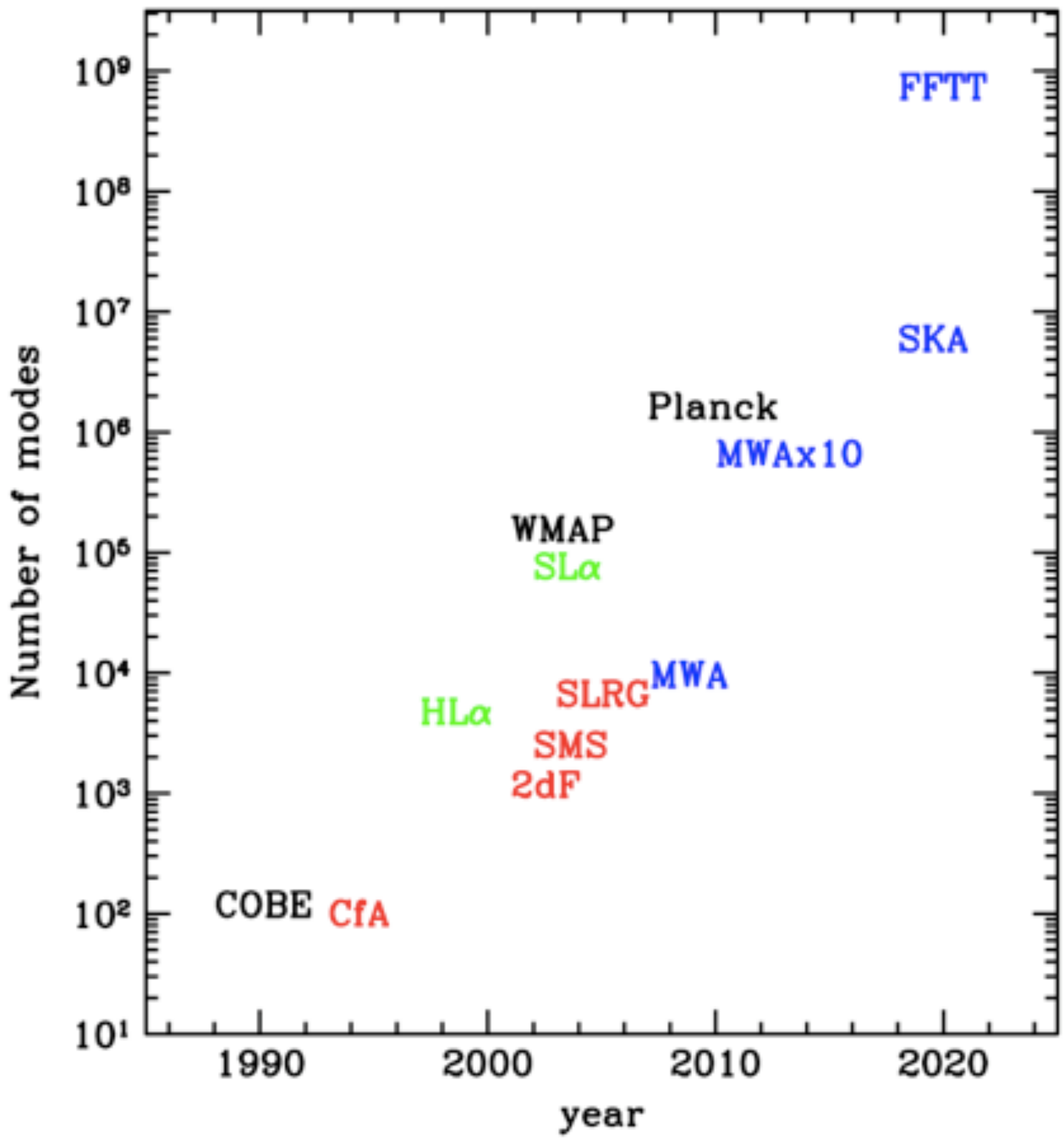
volume surveyed w/ S/N>1

number of linear modes

(depending of course on when it is built.)

Since LSS is 3-d it's inherent cosmic variance limits are less than that for 2-d CMBR maps.

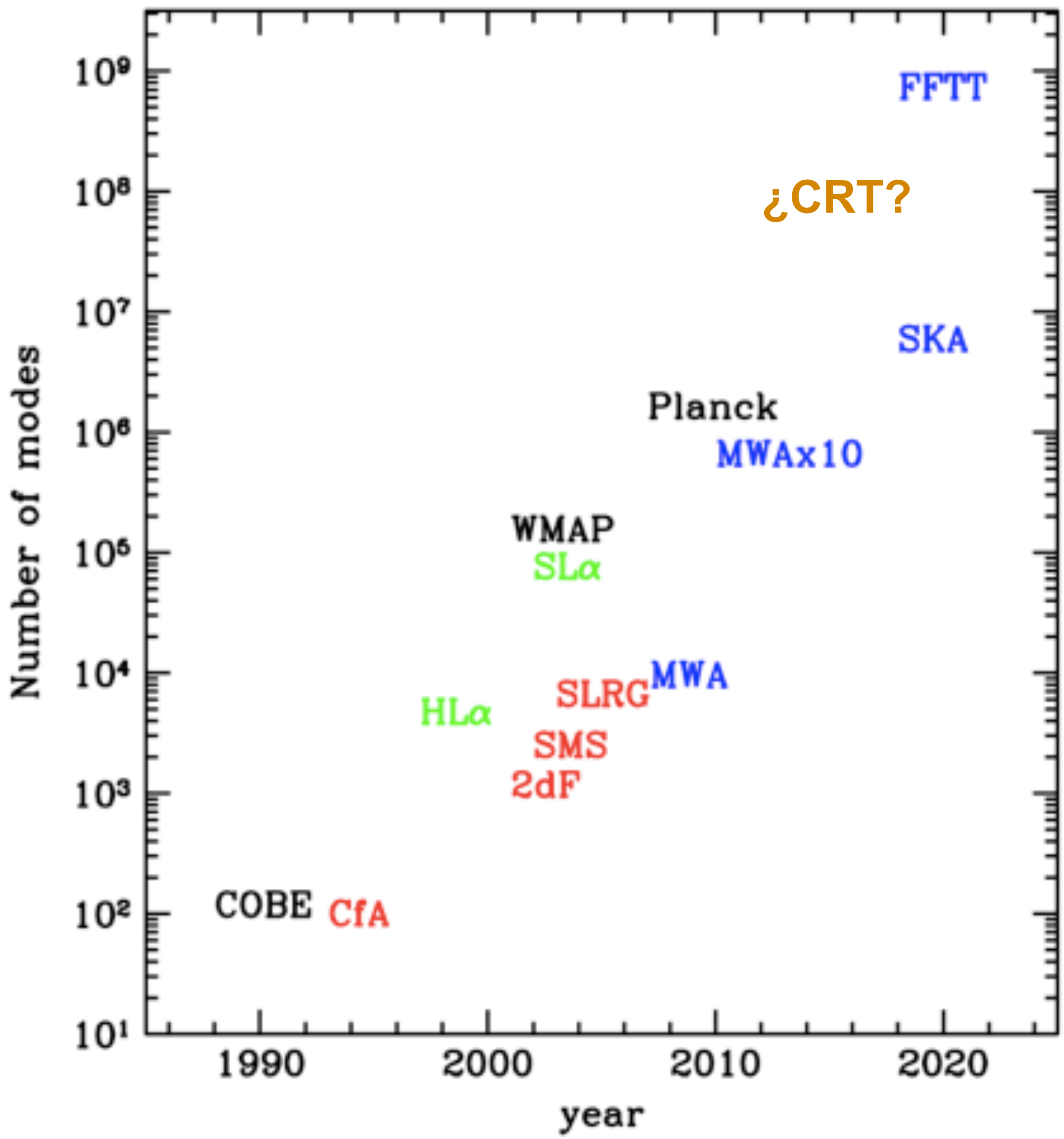
Sensitivity ~ 1/√(# of modes)



Tegmark Zaldarriaga 2008

Sensitivity ~ 1/√(# of modes)

Tegmark Zaldarriaga 2008



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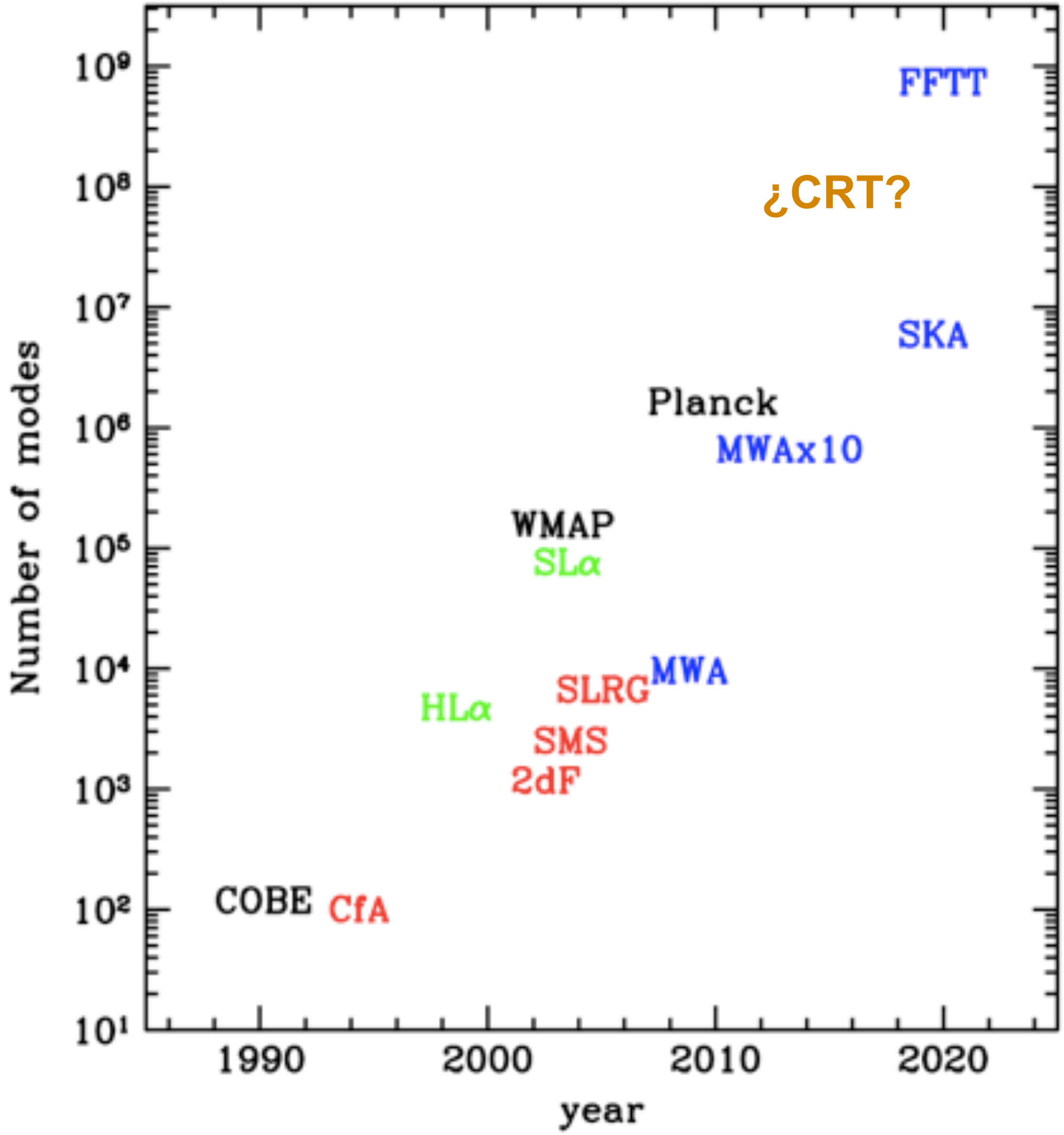
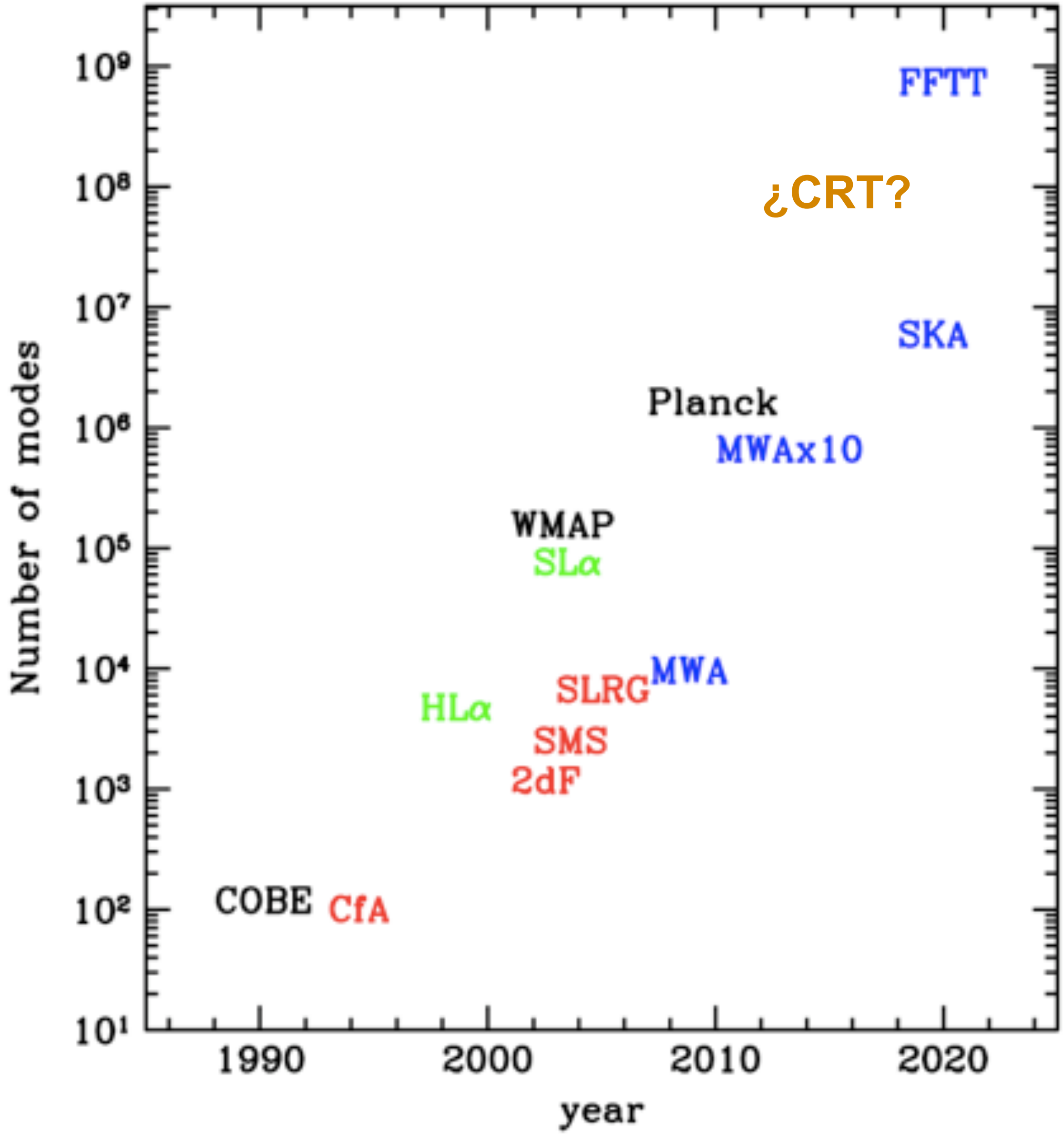


Tegmark Zaldarriaga 2008

Or course both quality and quantity matters!

Understanding systematic errors will be an essential part of the CRT program.

Sensitivity ~ 1/√(# of modes)



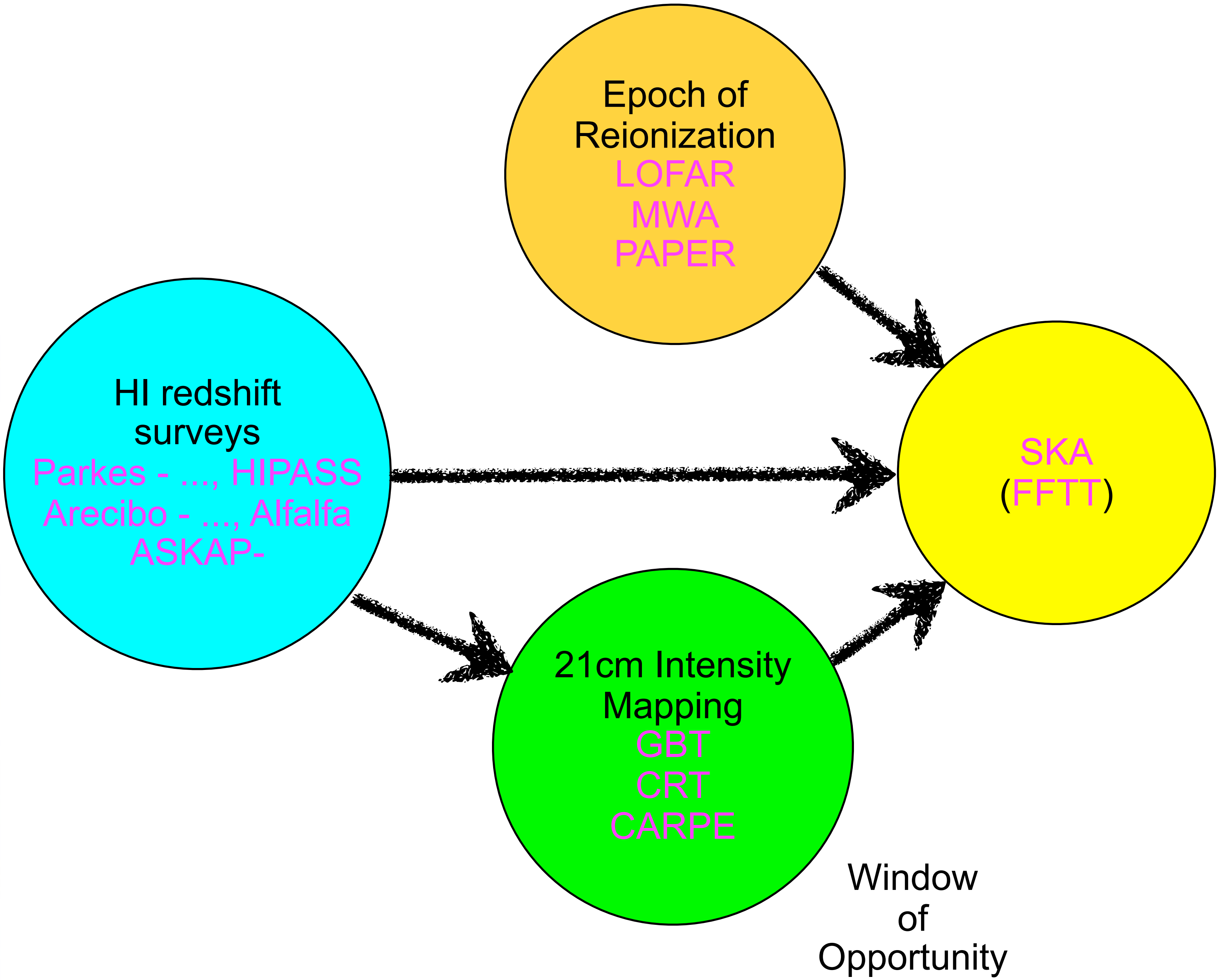
Tegmark Zaldarriaga 2008

Or course both quality and quantity matters!

Understanding systematic errors will be an essential part of the CRT program.

This project would allow FNAL to get in on the "ground floor" to the "era of 21cm cosmology".

Era of 21 cm Cosmology



Cosmic Cartography

Resolved galaxies

Unresolved galaxies

Gas - The Dark Ages

Epoch of Recombination

Galaxy Evolution

21cm

Synchrotron emission

Cosmic Magnetism

Other Science Goals

- Other science goals:
- Search for pulsars (should be a factor 5-10 more efficient than current surveys) – GR, gravity waves, etc.
- Evolution of neutral hydrogen in $1<z<4$ interval (synergy with NSF-funded ALMA, SDSS).
- Direct observations of proximity zones around bright quasars (synergy with SDSS).
- LSST+CRT value added catalog
- Tons of Galactic science.
- Search for transient phenomena.

The End

Additional Slides

Science with SKA (circa 2004)

KEY PROJECTS (3/5)

3. Strong-field tests of gravity using pulsars and black holes

4. The origin and evolution of cosmic magnetism

5. Galaxy evolution, cosmology and dark energy with the Square Kilometre Array

6. Probing the dark ages with the Square Kilometre Array

OTHER SCIENCE PAPERS

11. Strong gravitational lensing with SKA

12. Measuring changes in the fundamental constants with redshifted radio absorption lines

13. Sunyaev-Zeldovich effects, free-free emission, and imprints on the cosmic microwave background

14. Searching for intergalactic shocks with the Square Kilometre Array

19. The accretion history of the Universe with the SKA

23. From gas to galaxies

24. Predictions for the SKA from hierarchical galaxy formation model

27. HI imaging the low red-shift cosmic web

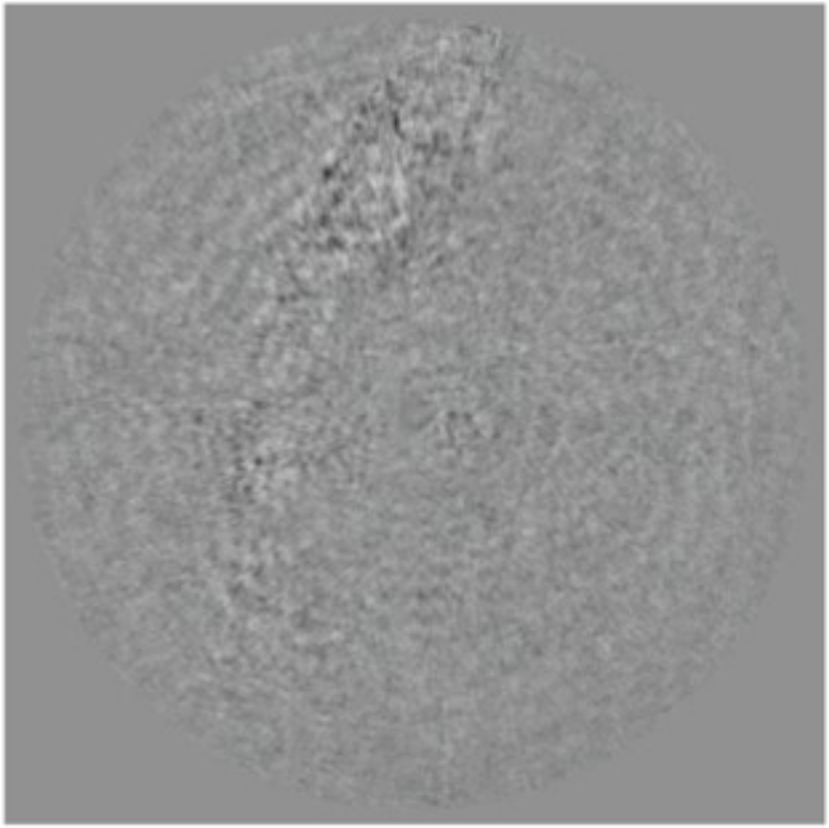
29. SKA observations of the cosmic web

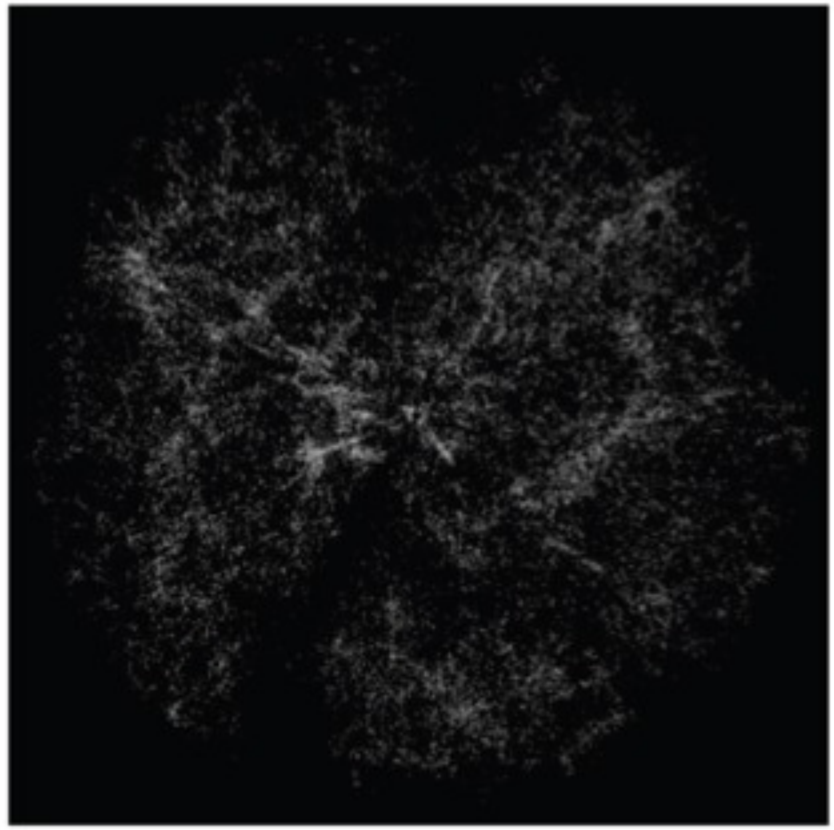
40. Strong-field tests of gravity using pulsars and black holes

44. Observing gravitational radiation with QSO proper motions and the SKA

49. Exploration of the unknown

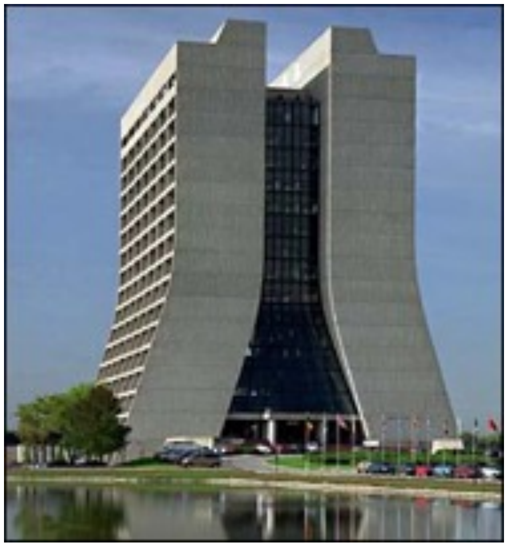
Already have...





Pen et al. 2008: x-correlation of HIPASS & 6dF (z~0.04)
Chang et al 2010: x-correlation of GBT & DEEP2 (z~1.0)

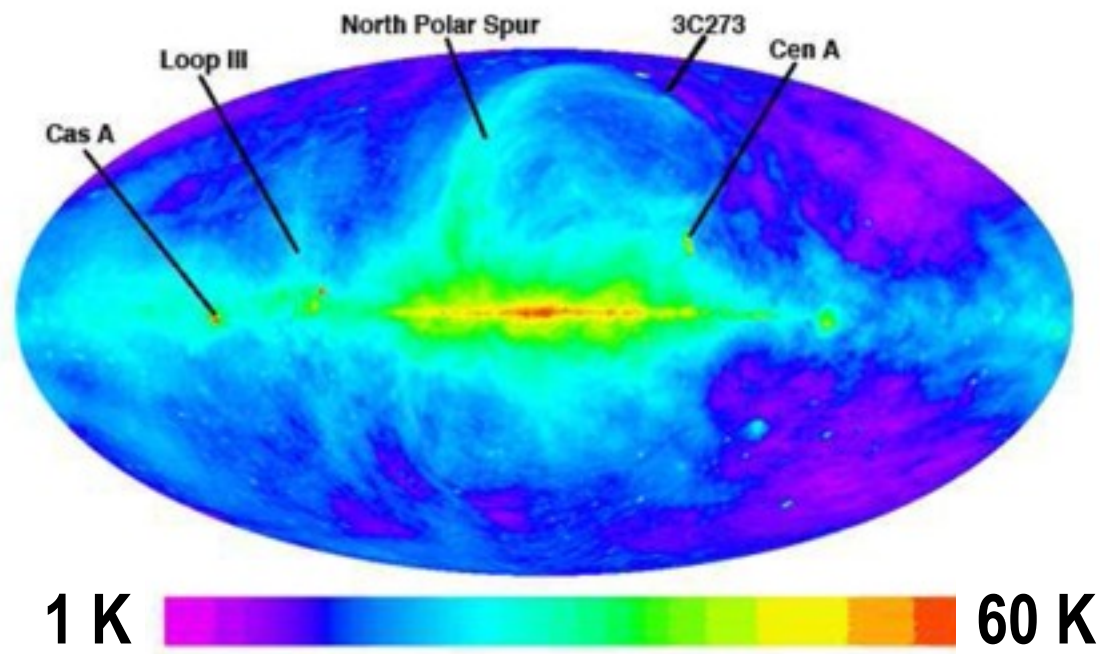
21^{cm} Experiment for the 21^{st} Century



Fermilab

Will It Be Done?

- The crucial difficulty of this project is in the weakness of the signal relative to foregrounds:
  - Galactic synchrotron
  - External radio galaxies
  - Galactic free-free



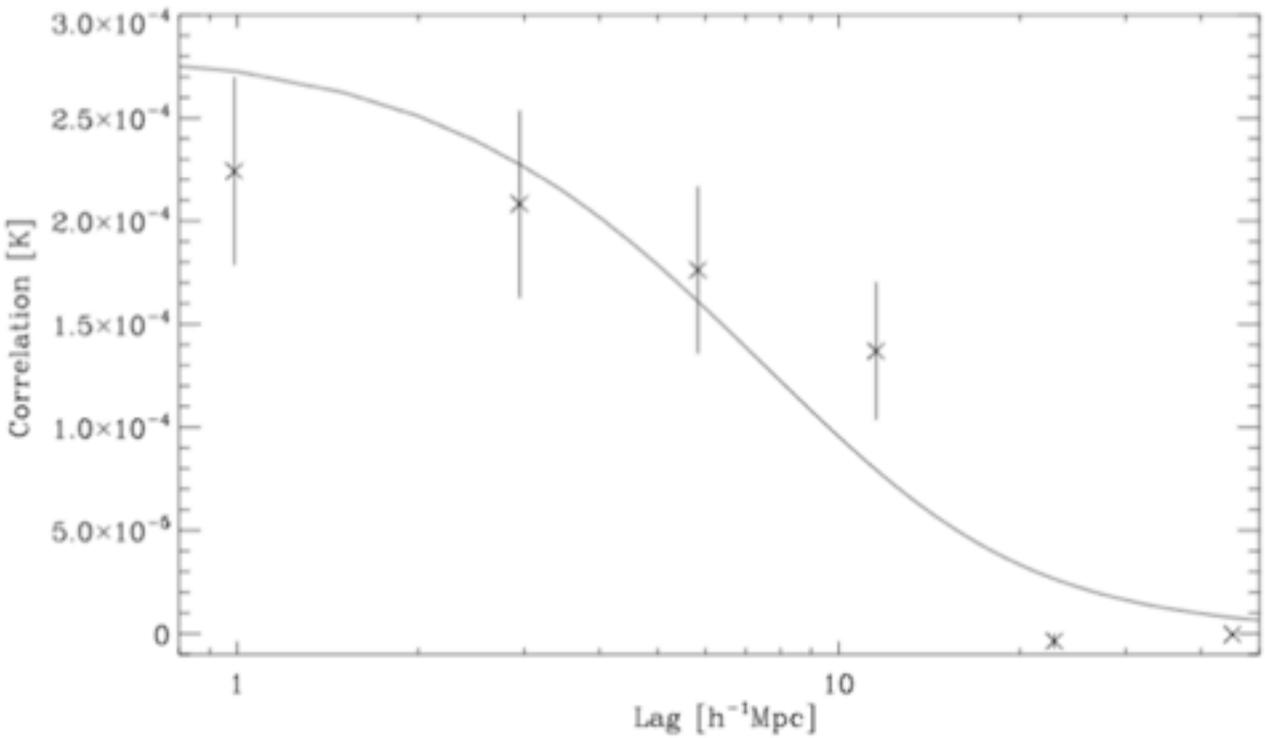
Why Fermilab?

- A window of opportunity exists if we move fast - competing, larger efforts will ***not*** produce results before ~2020 (if they are funded at all).
- No serious competing efforts in the radio BAO currently exist, but other groups are starting to organize.
- 3+ EOR 21cm experiments (similar technology, non-overlapping science goal).

Has Anyone Done This Before?

HI & Optical cross-correlation at z~0.8

- Shows correlation between hydrogen and Deep2 optical galaxy surveys to 10 Mpc



Chang, Pen, Peterson, Bandura, submitted

Cosmology By Cartography

To study cosmology we need to study the things in the universe: e.g. galaxies, clouds, *etc*.

These things are generated as random noise!

To characterize this random noise we need good statistics - *i*.e. large volumes, solid angle, *etc*.